Nuclear and Emerging Technologies for Space 2014
Infinity Science Center, Stennis, MS - February 24-26, 2014

Preliminary Analysis: Am-241 RHU/TEG Electric Power Source for Nanosatellites

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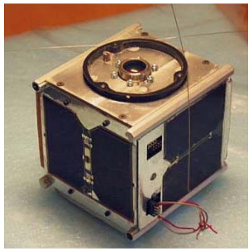
Nanosatellites (NanoSats)

- Nanosatellites (NanoSats) are small spacecraft in the 1-10 kg range, which present a simple, low-cost option for developing quickly-deployable satellites. CubeSats, a special category of NanoSats, are even being considered for interplanetary missions. However, the small dimensions of CubeSats and the limited mass of the NanoSat class in general place limits of capability on their electrical power systems (especially where typical power sources such as solar panels are considered) and stored energy reserves; restricting the power budget and overall functionality.

Mass: 46 kg



Mass: 1 kg

Staehle, R., *et al.*, “Interplanetary NanoSat: Opening the Solar System to a Broad Community at Lower Cost,” *JoSS*, Vol. **2**, No. 1, pp. 161-186, 2013.

CubeSats

- CubeSats are nano-satellites categorized by size and weight
  - 1U: 10cm x 10cm x 10cm and less than 1Kg
  - 2U: 10cm x 10cm x 20cm and less than 2Kg
  - 3U: 10cm x 10cm x 30cm and less than 3Kg
- Limited surface area restricts area for solar panels and power production capabilities
  - 1U: 1-2.5 Watts; 2U: 2-5 Watts; 3U: 7-20 Watts
- Power budgets for CubeSat subsystems
  - Primary CubeSat subsystems:
    - Attitude determination and control (ADCS)
    - Command and data handling (C&DH)
    - Communications
    - Electrical power supply (EPS)
    - Technical payload

Shifting Trends in CubeSat Usage

- Typical, past CubeSat mission scopes
  - Commercial-off-the-shelf (COTS) component testing in space environment
  - Novel technology testing (e.g., ion thrusters, radiation detectors)
  - Telemetric sensor data acquisition (e.g., atmospheric data, GPS locating)
- Increasing interest in CubeSats due to proven mission successes and low-cost imposed by strict design standards
- New, emerging CubeSat mission scopes
  - Trending towards useful scientific data acquisition (i.e., increased high-performance requirements for on-board data processing)
  - Trending away from simple verification and usage experiments

SpaceWorks_NanoMicrosat_Market_Feb2013.pdf

Am-241 RHU/TEG Power System

- United Kingdom (UK) evaluation of several isotopes have concluded that Am-241 is a good replacement for Pu-238 in space missions. Am-241 has a half-life that is approximately five times greater than that of Pu-238 and it has been determined that the neutron yield of a 241-AmO_2 source is approximately an order of magnitude lower than that of a 238-PuO_2 source of equal mass and degree of ^{16}O enrichment. It has been demonstrated that shielded heat sources fuelled by oxygen-enriched 238-PuO_2 have masses that are up to 10 times greater than those fuelled by oxygen-enriched 241-AmO_2 with equivalent thermal power outputs and neutron dose rates at 1 m radii. [1].
- Am-241 radioisotope heat unit and thermal electrical generator (RHU/TEG) are being developed in the UK as the electrical power source (EPS), where studies have identified Am-241 as the isotope of choice for a European program [2].
- The UK reports that Am-241 fuel can be produced economically and at high isotopic purity by separation from stored separated plutonium (Pu) produced during the reprocessing of civil fuel [3].

1. O'Brien, R. C., et al., "Safe radioisotope thermoelectric generators and heat sources for space applications," Journal of Nuclear Materials, 377, pp. 506–521, 2008.
2. Sarsfield, M. J. *et al*., "Progress on 241Am production for use in Radioisotope Power Systems," Paper **6750** in the Proceedings of *Nuclear and Emerging Technologies for Space 2013* Albuquerque, NM, February 25-28, 2013.
3. Ambrosi, R. M. *et al*., "Development and Testing Of An Americium-241Radioisotope Thermoelectric Generator," Paper 6780 in the Proceedings of *Nuclear and Emerging Technologies for Space 2013* Albuquerque, NM, February 25-28, 2013.

Am-241 RHU/TEG Power System

- In the US, the Idaho National Laboratory, Center for Space Nuclear Research reports [1] that:
  - Am-241 is available at around 1 kg/yr commercially,
  - Am-241 produces 59 keV gammas which are stopped readily by tungsten so the radiation field is very low. Whereby, an Am-241 source could be placed in among the instruments and the waste heat used to heat the platform, and
  - Amounts of isotope are so low that launch approval may be easier, especially with tungsten encapsulation.

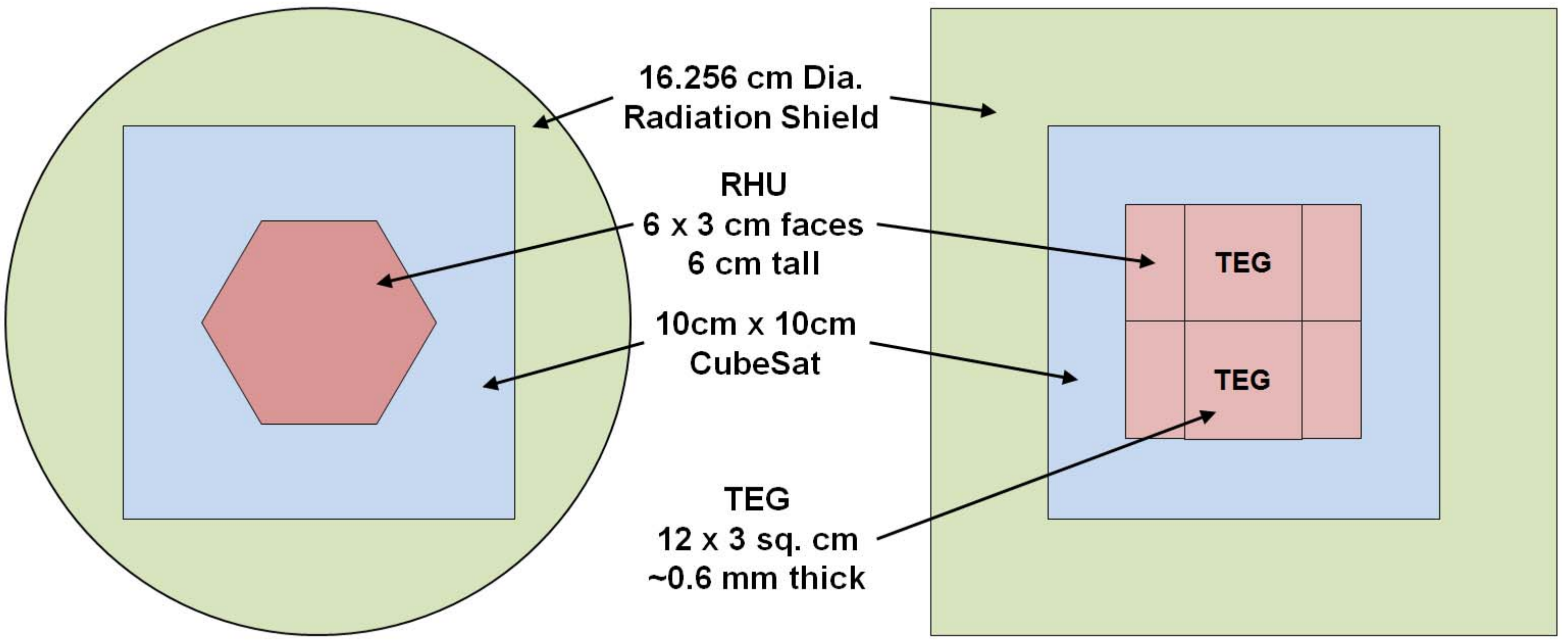
1. Howe, S. D., *et al*., “Compact, Low Specific-Mass Electrical Power Supply for Hostile Environments,” presented at the 9th Annual Polar Technology Conference, 2-4 April 2013.

Am-241 RHU/TEG Power System

- For these reasons, Am-241 is well suited to missions that demand long duration electrical power output, such as deep spaceflight missions and similar missions that use radiation-hard electronics and instrumentation that are less susceptible to neutron radiation damage.

5 We CubeSat Am-241 RHU/TEG PS

Radiation shielding: Outermost shield for neutrons would be composed of 5 cm thick boron loaded polyethylene



O'Brien, R. C., *et al*., "Safe radioisotope thermoelectric generators and heat sources for space applications," *Journal of Nuclear Materials*, **377**, pp. 506–521, 2008.

5 We CubeSat Am-241 RHU/TEG PS

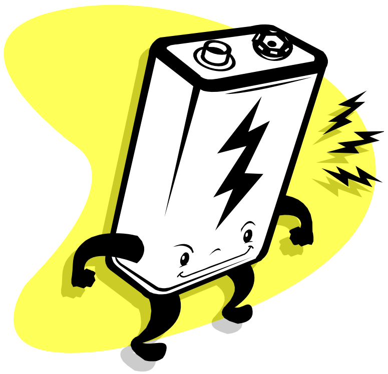
- To overcome the dimension limitation, part of the neutron shielding could be placed around the CubeSat while only in the carrier/launcher to provide adequate radiation safety during handling and ground operations, and left in the launcher after the CubeSat is deployed.

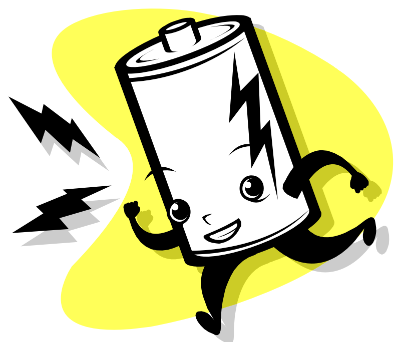
- For smaller Wattage (<5 We) RHU/TEGs, some reduction in the size would be expected. But the 5 cm thick boron loaded polyethylene neutron shielding required would still push the overall size outside CubeSat dimensions.

- Need to determine if the 5 cm thick boron loaded polyethylene neutron shielding would be reduced by the carrier/launcher.

Energy Budgeting Analysis

Arnold, S.S., Nuzzaci, R., and Gordon-Ross, A.,
"**Energy budgeting for NanoSat with an integrated FPGA**,"
Aerospace Conference, *2012 IEEE*, 3-10 March 2012.





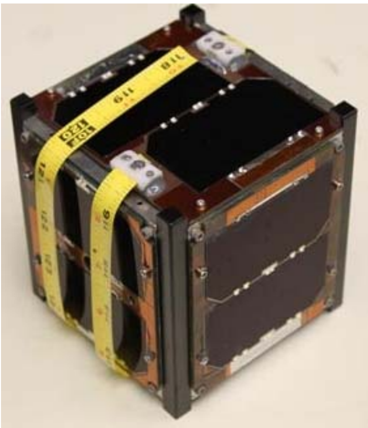
- 1U case study based on the M-Cubed (Orbital) project
- 3U case study based on the QuakeSat CubeSat (Orbital) project

1U Case Study

- 1U case study based on the M-Cubed (Orbital) project [1]
  - Power usage between 4-6 Watts on average [2]

1U Power Budget [1]

Subsystem	Description	Minimum Power (mW)	Maximum Power (mW)
ADCS	Passive Magnetic ACS	0	0
C&DH	Atmel AVR32 7002	-216	-292.5
Uplink	144 MHz, .33-m dipole	-616.5	-616.5
Downlink	437 MHz, .5-m monopole	0	-1000
Primary Payload	CMOS camera	0	-250
Secondary Payload	COVE board	0	-5088.5
Board	I/O power and loss	-227.5	-1254
EPS	4 Polymer Li-ion Batteries	-960	+4091
EPS	6 Solar Panels	+2010	+2010



[1] D. Bekker, T. Werner, T. Wilson, P. Pingree, K. Dontchev, M. Heywood, et al,"A CubeSat design to evaluate the Virtex-5 FPGA for Spaceborne Image Processing," Aerospace Conference, 2010 IEEE, Big Sky, MT, 6-13 March 2010

[2] P. Pingree, T. Werne, D. Bekker, T. Wilson, J. Cutler, M. Heywood, "The Prototype Development Phase of the CubeSat On-board processing Validation Experiment" in IEEE Proc. 2011 Aerospace Conference, Big Sky, MT, 2011

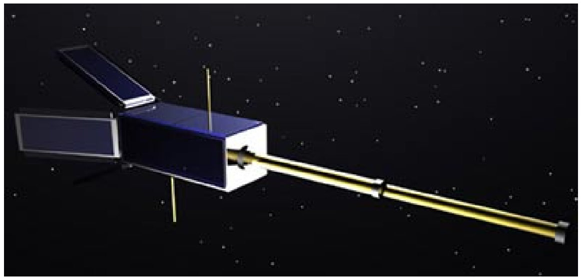
1U Energy Budget

- Power usage between 4-6 Watts on average is achievable with a 5 We Am-241 RHU/TEG power systems.
- Note. It is believed that the power budget equation used in [1] was not correct, which may have lead to it not working with the increase power requirement of the FPGA for the 1U case. With correction to the equation and using the 5 We continuous Am-241 RHU/TEG power source, it did work.

[1] Arnold, S.S., Nuzzaci, R., and Gordon-Ross, A., “Energy budgeting for NanoSat with an integrated FPGA,” Aerospace Conference, *2012 IEEE*, 3-10 March 2012.

3U Case Study

- 3U case study based on the QuakeSat CubeSat (Orbital) project [1]
  - Estimated maximum power consumption of 12.6 Watts when all components were operating.



3U Power Budget [1]

Subsystem	Description	Minimum Power (mW)	Maximum Power (mW)
ADCS	Passive Magnetic ACS	0	0
C&DH	Prometheus CPU	-2500	-2500
Uplink	Tek-net 9600 Baud-Rate Solid-State transmitter	-750	-750
Downlink		-1000	-1400
Primary Payload	Magnetometer	-600	-2200
Board	I/O power and loss	-850	-850
EPS	2 Li-ion Batteries	-8800	+11700
EPS	12 Solar Panels	+14000	+14000

[1] T. Bleier, P. Clarke, J Cutler, L. DeMartini, C. Dunson, et al, QuakeSat Lessons Learned: Notes from the Development of a Triple CubeSat, White Paper, June 4, 2003

3U Energy Budget

3U Equatorial Orbital

1st Iteration n=1	Energy Produced (J)	Power Stored (W)	Orbital Period (min)	Power Payload (W)	Operational Time (min)	Processing Time (min)	
Solar Panels	45,276	3.6	90.5	5.5012	10	218.18	
RHU/TEG	27,150					59.28	27%

$$t_{\text{processing}} = \frac{J_{\text{produced}} - P_{\text{store}}\left(\tau - t_1 - t_2 - \ldots - t_n\right) - \left(P_1 t_1 + P_2 t_2 + \ldots + P_n t_n\right)}{P_{\text{payload}} - P_{\text{store}}}$$

$\tau \equiv$ Orbital Period

$\mathrm{t}_n \equiv$ Payload Operational Time

$\mathrm{P}_n \equiv$ Payload Power

The P's in the equations are entered as **positive** numbers. This is opposed to the **negative** load power numbers given in the tables on slides 11 and 13.

3U Energy Budget

3U Equatorial Orbital

2nd Iteration	Energy Produced	Power Stored	Orbital Period	Power Payload	Processing Time	
	(J)	(W)	(min)	(W)	(min)	
Solar Panels	45,276	3.6	90.5	6.5012	129.89	
RHU/TEG	27,150				38.38	30%

$$t_{\text{processing}} = \frac{J_{\text{produced}} - P_{\text{store}}\tau}{P_{\text{payload}} - P_{\text{store}}}$$

Future Work

- Standardize a **5 We Am-241 RHU/TEG power system** for long term NanoSat missions.
  - Establish collaboration between NASA/MSFC and US/UK researchers developing Am-241 RHU/TEG power systems.
  - Establish Power Board Development at NASA/MSFC by:
    - Leveraging MSFC Solid State Ultra-Capacitor Development**, and
    - Leveraging MSFC Avionics Heritage.
- Flight Test by 2019 or earlier.

** For more information contact Dr. Terry Rolin at MSFC